IIASA
International Institute for
Applied Systems Analysis
www.iiasa.ac.at

Modeling of Technical Capacity and Cost Structure in Flexible Manufacturing Systems

Simons, M.

IIASA Working Paper

February 1990

WORKING PAPER

MODELING OF TECHNICAL CAPACITY AND COST STRUCTURE IN FLEXIBLE MANUFACTURING SYSTEMS

Magnus Simons

February 1990
WP-90-09

IIASA
International Institute
for Applied Systems Analysis

MODELING OF TECHNICAL CAPACITY AND COST STRUCTURE IN FLEXIBLE MANUFACTURING SYSTEMS

Magnus Simons

February 1990
WP-90-09

INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS
A-2361 Laxenburg, Austria

FOREWORD

This paper presents work done during the summer of 1989 by a member of the Young Scientists Summer Program (YSSP) at IIASA. It is of special interest to those involved in the CIM project, and its collaborators.

Prof. Robert U. Ayres
Project Leader
Computer Integrated
Manufacturing

Prof. Friedrich Schmidt-Bleek
Program Leader
Technology, Economy, and
Society

ABSTRACT

The purpose of this paper is to create a basis for modeling of technical performance and cost structure in FM-systems. Time sharing between manufacturing phases and the cost of the system parts and implementing activities are considered. The technical performance is divided into theoretical capacity and difficulties and trade offs. The flexibility is also considered. The costs are studied separately for nine features. In addition to the hardware, software and working costs are the effects of standardization and modularization studied.

In the second part of the paper the FMS-model of Ranta and Alabian has been critically reviewed and some ideas for modification are presented. Finally some of the lessons learned during this work are listed.

TABLE OF CONTENTS

MODELING OF TECHNICAL CAPACITY AND COST STRUCTURE IN FLEXIBLE MANUFACTURING SYSTEMS

Magnus Simons

Technical Research Center of Finland
Laboratory of Electrical and Automation Engineering
Otakaari 7 B
SF-02150 Espoo, Finland

1. INTRODUCTION

Flexible manufacturing systems (FMS) are becoming more and more popular in the manufacturing industry. The automatic use, the high performance and the ability to produce good quality products are characteristics of a production system that are hard to resist. But the implementation of the new technology does cause problems. Technically the FMS is much more complex than any other machines used in the workshop. This also affects the organization. Economically the FMS is a large investment and the benefits are often difficult to quantify. This creates a great need for different decision support systems for system designers and company management.

In a early stage of the investment process the designer need to do a rough estimation of the costs of the investment. At the same time he has to know the connections between the performance of the system and the costs. The estimation of these connections is a multi-level and multi-objective task, which demands a great deal of knowledge about the FMS-technology. At the International Institute for Applied System Analysis (IIASA) Ranta and Alabial have developed a model for estimating the cost-efficiency of a FMS-investment.

This paper is a result of working with the FMS-model described in (Ranta, Alabian, 1988) and (Stam, Kuula, 1989). To get a full view of the model and the problems behind it the reader is advised to get acquainted with these working papers. Here the focus will be given to the input of data and the structure of the data.

In order to study the input data of the model we start by giving a description of the system being modelled. We look at the different parts of the system and their functions, the problems and the possibilities to vary the design of the FM-system.

In chapter 3 is given some criticism to the existing model and in chapter 4 some new ideas are presented.

2. THE FMS-DESIGNERS DILEMMA

The first step in a investment process is usually the realizing of a need to change the existing facilities. The second is to find different options for the future and the third is to make rough calculations of the existing possibilities. After this comes the investment decision, the actual planning of the investment object, the realization and the use. This paper concentrates on one option for the third step; the rough calculation of costs and efficiency of a investment in FMS.

Rough estimations of cost and performance of a FMS is not a easy task. Very often the planner lack the experience to make proper estimations for costs and performance and especially for the connections between these two. The purpose of this study is to give a structured picture of the reality behind the model and how it can be connected to the data the planner has available to base his estimations on.

The data available in a very early stage of the design process is the following:

- The process planner will base his work on the existing data about the product design, the production volumes and the need for flexibility. These are usually available from marketing, product construction and top management.

- The flexibility of the production system can have a strategic impact on the company level. There for the top management and the marketing are likely to demand certain performance in delivery time, batch size and size of part family. The top management may also have a view of how fast the parts in the family has to be renewed and how the production volumes will change in the future.

- The drawings show the shapes, the sizes and the tolerances of the products or parts. Based on these the process planner can decide what kind of machines and tools are needed and how the part should be produced. From the total bunch of drawings in the part family and the production volume data he gets the information necessary to estimate the total need for physical production equipment. The number of machines can roughly be estimated on the base of data on machine tool characteristics available from vendors. The planner also need a good knowledge about tooling, transporting and fixing.

- In addition to these data and demands the planner can, with the help of FMS vendors and machine tool producers, get rough estimates for cost per machine, per tool and for the transport system.

From the available data the investment planner is supposed to create the information on total cost and cost structure for the investment.The relations between the performance and the cost of the investment is also of great interest. The question is:

> How will the total cost react on certain changes in the production volume, the through put time, the batch size or the size of the part family? How can minimum costs be achieved within the given constrains?

The major problems the investment planner will meet with is the estimation of the non-availability time and it's effect on the total production, the costs for software and training and finally the time and money needed for the implementation of the system.

In this paper we will take a look, from the designers point of view, at the design of the machining process in the FM-system. We divide it into the technical capacity of the system, and availability. At the end we look at some trade offs in the design.

In an attempt to structure the capacity we will use the assumption from the existing model that the critical resource in the production is time (Ranta, Alabian, 1988). We will also divide the production system into two parts: the value adding part and the supporting. By the first one we mean the machining processes and by the supporting operations the transporting, information management, maintenance etc. By dividing the total time into parts we try to find the suitable performance of the value adding operations. The theoretical starting point is the possibility to use 100 % of the time for these operations. In reality is this very difficult to realize and hardly profitable.

After looking at the design of the value adding operations we will consider the real problems of the design process. These are the availability off the system and the design trade offs. Contradictory to the design of capacity the availability has to be studied for all the system. In stead of the value adding and supporting operations we divide the system into the functions performed by the different pieces of equipment.

Last but not least we will have a look at the costs for the system. The total costs are divided into specific cost factors, which in turn depend on cost per equipment, and the number of different pieces.

2.1 The technical capacity of the machining process

The total time in the value adding operations can be divided into actual tooling time, overhead time, batch change time, waiting time and disturbance time. The tooling time is the only phase in which value is added to the product and there for it should be maximized. The other parts have a negative effect on the out put of the production system and should be kept as short as possible or they should be performed in parallel with the value adding process. The number of times these appear is dependant on the batch size and the complexity of the parts.

The tooling time in a workshop for metal parts is the time when a tool is actually cutting and shaping the work piece and the rapid feed movements between cutting movements. Tooling time is dependant on the shape of the surface being machined, the tolerances needed, the material, the tool and the characteristics of the machine tool. These are spindle speed, feed rate, control of machining routs and reliability of machining function.

The machining operations are heavily dependant on the shape and design of the part. Both the surface being machined and other closely connected surfaces affect the use of power and speed in machining. The machine control unit often restricts the possibilities for making complicated shapes. The shape of the part also sets restrictions on the shape of the tool.

The tolerances between different surfaces in the part affect the choice of machining operation; the number of operations and the type of finishing operation. The surface finishing and the material of the part set restrictions for use of machining speed, feed rate, depth of cut, tool material, shape of cutting edge of the tool and usage of coolants for transportation of scrap and for cooling down the tool and the work piece.

The material of the work piece is the most important factor in deciding the machining speed. With different tool shapes and material, and through use of coolants can the speed be increased or decreased, but only to a limited extent.

The overhead time is the time a machine tool is occupied with other than actual tooling operations. These are changing of tools or work pieces, removal of scrap, measuring of work piece or tool.

Batch change time occurs between the machining of different batches. During this time the NC-programs for the machining process, the fixtures and the tools has to be changed either automatically or manually.

Waiting time occurs when the supporting operations are not able to supply the system or a machine tool with the parts, equipment or energy needed for the value adding process.

The disturbance time is the time when the machine tool can not be used due to disturbance or maintenance. In the following chapter we will take a closer look at what lies behind it.

The first step in the design process is to set goals for the downtime and the waiting time. The time left for machining divided by the total time is the utilization rate of the system. In flexible manufacturing system this figure is often about 80 - 90 %. The non-availability of the systems is usually about a 3 - 5 per cent.

After setting the goals the designer can use the production figures and the machining data based on the product and part drawings to calculate the need for machining capacity. All the different kinds of machining has to be taken into account. The number of machines will be calculated by dividing this capacity need by the capacity of the machines calculated for the utilization rate set as a goal in the previous phase.

The numbers and capacity of the transport system, and other supporting systems can also be roughly calculated using the same method.

The capacity calculations presented here are only very rough approximations of the characteristics of the real system. A very important aspect left out is the coordination of the different operations in the system. In reality this will play a very important role for the capacity and flexibility of the FMS. It is possible that the needed calculations can be done fast for small systems, but computer simulations are often necessary for bigger FM-systems.

2.2 The reality -problems and trade offs

The complexity of the FMS makes the reality a lot more uncertain than what is described in the previous chapter. One of the biggest problems for the FMS-implementor is to achieve the availability goals set in the beginning of the design process. He has to know how the different pieces of equipment is built and how it works and he has to know the connections between the parts in the system. The design process will be even more complex when taking into account the different trade offs between parts and their affect on characteristics of the system.

2.2.1 Availability - planning the quality of the functions

To study the availability of the FMS it has to be broken down into smaller pieces. We study the physical equipment part for part and for each one we define a function. Assuming that the designer of the system has succeeded in integrating all the parts in the system, we study the quality of the functions performed by the different pieces of equipment.

The main physical parts in the automatic production process in a FMS are the machine tools, the tools, the software, the control system, the transport and support system, the pallets and fixtures. In addition there is the raw material, the final part and scrap. Disturbances can be caused by any of the parts participating in the process and there for the availability is dependant on the quality of each of the functions performed by the participating parts.

The functions performed by the components in the FM-system are listed below:

- The function of the machine tools is to perform the machining, work pies changes and batch changes.
- The function of the tools is to cut the material.
- The software is a part of the steering and control system in the FMS. The task of the system is to manage the motion in the machine tools and in the transport systems and to manage the information on parts and equipment in the system.
- The function of the transport system is to transport work pieces, finished parts, pallets, scrap and tools.
- The function of the help systems is to support the machining function.
- The function of the pallets and the fixtures is to fix the work piece properly in the machine tool.

The quality of the functions is a mixture of the physical characteristics of the equipment, the degree of control and possibilities for regulating, the quality of the installations, the quality of related functions and the management of the function.

<u>The machine tools, the tools, the software, the control system, the pallets, the fixtures and grippers</u>

Disturbances are very likely to occur if and when there are mechanical changes in tools or other physical equipment. There for it is very important that the quality of the hardware is related to the quality of the parts being produced. The same thing is true for the electrical equipment.

The physical quality of the equipment is determined by the process in which it was designed and produced and the quality of it's components. Since most of the components in the FMS are designed and produced outside the investment project the planner is less concerned with how the quality of these is realized than with the fact that the product he byes can perform according to the standard set for the system. In the planning process of a FMS the most important feature is the over all performance. The planners task is to chouse the right components, not to produce them. This is usually true for machine tools, transportation systems, robots and some other hardware pieces.

There are parts in the system that often can not and ought not to be bought as "turn key" components. The control system is often built of standard components, but the layout and communication networks are taylored for the FMS in question. The quality of the system is, of course, depending on the quality of the components, but the major issue is to get it to fit the purpose it is installed for. In other words; the design of the control system strongly affects the quality of the function in the FMS.

The quality of the software is also a major concern of the planner's. The reliability of software is the main problem. "Bugs" can come in to the software from the data it is based on, from software design, from the physical programming or as inputs from related software or from operators. Often the disturbances occurs in rarely used control software or in special situations.

To increase the reliability of software there are different tools. The programming of NC-program for machining of simple geometrical surfaces is usually done automatically with the help of interactive programming units on the machine tools or in a special department for this purpose. More complex parts are still programmed manually. For checking of programs you can have a special program looking for "bugs". The reliability of the function performed by software can also be improved by redundancy. This means that two or more different software packages perform the same task.

The quality of the function of a piece of equipment is not only decided by it's material and design, but also by the possibilities to maintain function quality by regulating the performance. The possibilities to supervise and to control fluctuations in the function are often the only way to obtain a high performance level.

The quality of the function of one component is not only due to how well it is produced, but also to how it is implemented. In a production system there are two kinds of components: 1) the fixed hardware and software 2) hardware, software and work pieces, that is changed frequently.

The first group is installed in the implementation stage by either system vendors or operators of the system. Their performance and understanding of the equipment will be most relevant to the performance of the FMS.

Since the tools are changed quite often, a fast and exact fixing or installing of the tools in the machine is very important. The tools are usually switched automatically by a robot or manipulator and the quality of the fixing of the tool is mainly depending on the design and performance of the fixing cone on the tool and the fixture on the machine tool.

The installation of software in the system is done either manually or automatically depending on the kind and purpose of the software. The NC-programs for machining of parts are usually installed automatically. The quality of this function depends on the software and hardware constructed to transport and install these programs. Other software is installed manually and the quality is related to the operators performance.

The quality of interrelated functions will affect the performance of the function if their output is a input to it. If the quality of the input is too low or irregular it will cause problems in the process.

The interrelated functions can be defined as follows:

- The related functions that can affect the machine tool's function are all the other functions mentioned above.
- The related functions are the machine tool and the steering of the machining movements, the work piece and the scrap.
- Related functions are the machine tool function and the function of the transportation system.
- Related functions to the transportation are the control system, the machine tools and the pallets, to the pallets and fixtures the transport system, the work piece and scrap.

Operating machine tools, storing, maintenance, cleaning and improving of functions is here referred to as the management of the functions in the FMS. These are the human activities in most FMS and they have proved to be very important for the performance of the system. Not only for the quality of the functions and the quality of the end product, but also for the flexibility and capacity of the system.

The quality of management depends on the know-how and the feeling the operators have for the system. This can be enhanced by training and by participation in the design and implementation process. Also design factors like standardization and modularization are likely to play a role.

The work piece and the scrap

The work piece and the scrap set demands on the production equipment. Both on hardware and on software. There for the complexity of the work piece and the presence of scrap has to be taken into consideration when designing the production system. A very important aspect in managing the performance of the production system is the managing of the quality of the raw material or work pieces.

The complexity of the part consists of the different surfaces that has to be machined, the tolerances of the different geometrical shapes and the material of the part. One aspect of complexity is the fixing of the part to a pallet or in the machine. The complexity can cause disturbances by setting to high demands on equipment, like tools, machines and their control systems. Very complex parts can make the NC-programming more difficult, too. Difficult surfaces are, for instance, deep holes with small diameters, parabolic surfaces and other shapes that need three-axis contouring.

The number of surfaces and the tolerances are also related to the size of the software needed. The software it self is of course not a cause to disturbances, but the bigger the software is the bigger are the possibilities for "bugs".

The fixing of the work piece can force you to machine in awkward positions, which will complicate the programming and the use of tools. A poorly designed fixing can force you to use special tools and equipment.

The quality of the raw material or of the part in the machine can limit the possibilities for efficient and safe machining. If the quality of the material is poor or heterogeneous it is going to affect the speed of machining and it may cause damage in tools or other equipment. It has to be mentioned that a poor product can cause a lot of trouble not only in the machine where the defect appears, but also in later machining sequences. It is a fact, that the efficiency of existing FM-systems is very much due to the improvement in raw material.

Scrap can cause problems in the machining process by disturbing the functions of the tools, machines or the control systems. Scrap can also change the quality of the part being produced, without disturbing the machine functions. Finally scrap can cause alarms and stoppages by disturbing the control system although the process is not affected.

The critical functions

There are functions that are more critical for the performance of the system than others. The reason is often that the automatic equipment is not yet good enough to perform this function properly. Sometimes the problems arise because of lack of experience among the operators. Functions considered as critical are the batch change, the gripping and automatic fixing of work pieces and the management of disturbances during unmanned production.

Batch change means that the programs, tools and in lathes often also the grippers for fixing of the part and the robot gripper has to be changed. In machining of non-rotational parts the pallets are often standardized, and their fixing in the machine tool do not need any changes. The many levels of change gives the possibilities for disturbances a lot of room. In a Finish case study the rate of disturbances was over 20 % higher during and immediately after a batch change than during the continuing machining of the batch. If the product was new the rate of disturbances was more than 100 % higher. This was during the first year of full scale operation and the number are very likely to decrease. But the trend was very visible.

Scrap is a major reasons for disturbances in the control system. But there are also others. For instance mechanical and electrical disturbances in the control equipment often interrupt the machining functions. Incorrect measurements due to internal or external factors, like heat or vibration, are also common.

The handling and fixing of parts can be a problem in lathes. The coordination between the robot, the pallet and the machine tool and the tolerances in their location has to match the control system of the robot. This sets high demands on the technical equipment. Manual interaction in a robot cell has often been the course of inexact coordination, because the small space in the cell makes it very difficult to move without bumping into the equipment, and hence mixing up the programmed reference points in the robot.

Management of disturbances during unmanned production is often the most critical factor when deciding on whether unmanned production in second or third shift should be used or not. If the automatic management of the disturbances is not good enough, the down time can be longer than the effective unmanned production.

2.3 Coping with the difficulties and trade offs

The ways to cope with and to prevent disturbances are perhaps as many as the system operators in the world. The most common and systematic ways are mentioned below. To prevent disturbances you can organize preventive maintenance, cleaning of work place and work piece, redundant hardware and software and to train the operators to maintain a high utilization rate of the system. The possibilities are many and they leave a lot of room for design and cost trade offs.

The possibilities to do effective maintenance on a FM-system is very heavily dependant upon the organization of the maintenance functions. Coordination of spare parts and maintenance people/know-how is essential for fast operations.

On the hardware side there are a few methods to support fast maintenance of production systems. Standardization of components will increase the availability of spare parts. Modularization allows you to change a part of the system, without having to deal with the system as a hole. Redundancy makes it possible to perform maintenance without disturbing the actual production functions.

Most machine tools are equipped with some kind of tooling control. In addition a lot of different technical solutions are available of supervising of different operations in the production system. With the help of a central minicomputer can the information from these be transformed to signals for automatic sub-systems aimed to prevent or correct disturbances. One example is the Automatic Tool Changer (ATC), that changes a broken or worn-out tool for a new one.

The trade off between tooling time and batch change time is related to the flexibility of the system. Tooling time can be maximized by minimizing the time for batch change. The ratio between capacity and flexibility is a strategic matter, that has to be decided at the top level in the company. If capacity has a higher priority hard automation can be considered in stead of FMS.

Tooling time can be improved by changing the characteristics of the part. Design, tolerances and material has to be related to the machinery used in the manufacturing process. This is a very important aspect when designing the organizational contacts between designing and manufacturing departments. The trade off in the designing process of the production system can be said to be the balancing of on one hand the machine tools and the coordination of the productions flow and on the other the product characteristics. If the design can't be changed the characteristics of the machine tool will determine the tooling time.

The trade off between capacity and flexibility is at the same time a trade off between skilled or non-skilled work force and determines the level of automation. If the flexibility requirements are high, the need for skilled human work will be high. The reason is the constant need for changes in both hardware and software and the reliable performance of these and of the other system functions. Highly skilled operators and a comprehensive control systems are the best means for coping with these situations.

There is also a trade off between manual and automatic machining.
The automatic tooling functions are often slower than the manual ones, but a higher utilization of the machines in automatic system makes it possible to have a higher output. The automatic productions system can work unmanned during lunch breaks, night shifts and week ends.

The relation manned/unmanned production also reflects the flexibility of the system. Although many users of FM-systems say that the set up time in their system is zero, the truth in most cases is that flexible production needs more time than continuing production in large batches. Time is spent for set up for new products, for disturbances due to set up and for testing of new programs and tools. The extra time needed for this is available in a automatic system.

The skills of the personnel are related to the system they work with. When talking about trade offs in implementation of FMS the main question is turn key versus do-it-your-self systems. In the later case the accumulation of knowledge during the build-up and start-up phases will make future operation and changes faster. The impact of standardization and modularization on the skills of the operators should also be mentioned.

2.4 Costs

Looking at the costs for the different parts of the investment we will start with the actual investment object, the product you pay for, and then relate this cost to the data available during the planning stage. We will notice that the cost of the system and it's parts are very much connected to the different features of the design process. Standardization and modularization are not only technical design features, but will also affect the costs of the system.

2.4.1 Tooling cost

The investment costs for tooling is dependant up on costs per tool and the number of tools. In addition there will be costs for maintaining, managing and pre-setting of the tools.

The cost per tools is affected by the following factors:

-material
-tool shape, tolerance
-size
-standardization
-modularization

The material of the tool is connected to the material of the work piece, tooling speed and tolerance. By using material of better quality you can increase the tooling speed without increasing the risk for disturbances. This will, of course, increase the tooling costs.

The shape of the tool, and especially the tolerance of the cutting edge, will determine the special tools needed to produce the tool and the production time. The higher these demands are the higher will the production costs be.

The size of the tool will mainly affect the material costs, but also the transport and storing costs can be affected.

Standardization of tool design can decrease the time and money spent on making new tools. If the tools or some parts of it are standardized designing costs can be minimized.

Modularization of the tool means that the number of parts needed will decrease. Modern tools for metal cutting often consists of two parts. These are the cutting edge for the material removing and the tool holder for fixing and positioning of the tool. The wear on the tool holder is usually very small and there for they can be used for a longer period of time and for different machining tasks. The cutting edge will be worn and has to be changed. Often so called tool inserts are used. They have multiple cutting edges and can be used for different purposes.

The number of tools depends on:

-number of different surfaces in part family/standardization of part design
-production volume
-number of machines
-standardization of tools
-standardized material
-modularization of tools
-maintenance of tools/control of tooling functions/ cleaning of work place
-management of tooling functions

The design of the part is crucial for the number of tools needed. If the design consists of a lot of different shapes and complex geometrical features, the number of tools will increase accordingly. Standardization of design features and simplification of design are the most effective ways to cope with this problem.

Standardization of work piece material and tool design will also decrease the number of tools needed.

The negative side of standardization is that it can decrease the effectiveness of the machining operations and limit the possibilities to produce customized products.

The effect of modularization was mentioned earlier.

The number of the machine tools and the management of the tools will together with the desired flexibility set limits for the minimum amount of tools. If, for instance, every machine is expected to be able to perform all of the machining functions needed in the part family, every machine has to have excess to the needed tools. This can be done in many ways. Every machine can be equipped with a tool magazine for all kinds of tools, or there can be a system transporting the tools from machine to machine. The number of tools in the first case is directly related to the number of machines and will be higher than in the other case, where the production volume and the coordination of the process are the major factors in determining the number of tools. But in addition to the tool costs there is the costs for the transport system.

Tool break down is often due to lack of proper cleaning of the work place, maintenance or control. By providing these functions you can decrease the tooling costs and in the same time improve the availability of the system. Of course there will be additional costs.

Maintenance and pre-setting of tools often need special equipment. The costs of these has to be considered in this context, too.

2.4.2 Pallet and fixture costs

The pallet and fixture costs can be divided, like the tooling costs, in number of pallets and fixtures and the costs for one pallet or fixture and maintenance costs.

The cost per pallet or fixture depends on:

-size
-complexity of design
-tolerances
-material.
-standardization
-modularization

The size is determined by the size of the work pieces, the number of work pieces on one pallet and the work space in the machine tool. The size and the material chosen are also depending on the machining forces.

The design of the pallet and the fixture is closely connected to the shape of the part being machined. Very often the fixtures has to be tailored for a certain part or part family. Standardization and modularization is getting more and more common, but there will probably always be parts of the fixing equipment, that has to be dedicated to the part family. The pallets are today often standardized.

The tolerances needed in the design of the final part set demands for the fixing of the work piece. The location of the work piece in respect to the working tool, the prevention of movements due to the machining forces, the transportation of scrap and the affect of fixing forces on the raw piece or the finished part are things that has to taken into account in the design of the pallets and fixtures.

The choice of material depends on the construction, the machining forces and other physical phenomena like temperature, vibrations and impact.

The number of pallets and fixtures are determined by:

-the number of different parts
-their order of machining sequences
-number of parts per pallet
-batch size
-production volume
-number of machine tools
-unmanned production
-standardization
-modularization

The parts in the family are fixed to the pallets according to the batch size. If the parts are small it is common to have the hole batch fixed to the same pallet. It is also common to have the hole part family or a certain part of it fixed to the same pallet in batches of one. This is possible if the machining sequences are the same or similar.

The standardization and modularization of the pallets and fixtures has the same effect on the numbers as was the case with the tools. The more parts that can be fixed to one pallet, the less pallet are needed.

The production volume, the through put time and the number of different machine tools or machine tools performing different machining tasks affect the number of pallets and fixtures. In an FMS every machine tool should at all times have one loaded pallet waiting, when the part in the machine is ready. In theory this means two pallets per machine. Through coordination between machines this number can sometimes be reduced without affecting the utilization rate of the machine tools.

The through put time consists of machining and waiting time. The more the parts has to wait during the process, the more pallets and fixtures are needed.

The number of pallets and fixtures set limits for the time of unmanned production. The number of loaded pallets stored in the beginning of the unmanned period is determined by the phase times for the parts produced and the time for unmanned production.

The design of the pallets and fixtures differs very much between rotational and non-rotational parts. For rotational parts the pallets are often very simple, but the fixing and handling of the part between pallet and machine tool is more complicated. The handling is usually done by a robot. A very important part is the robot gripper that places the part in the machine tool's fixture. The tolerances of the pallet and fixing equipment of a non-rotational part has, for the rotational part, to be designed into the functions of the robot and it's gripper.

2.4.3 Software costs

The software in a FMS can be divided into NC-software for the parts, control software of the machine tools, software for production management, software for the over all control of the system and software for operating the machine tools and the transport system. Sometimes production planning is integrated into the system. The size, complexity and the number of these different types of software are partly dependant on the same factors, partly on different. We will here consider the following factors:

- -size and complexity of the part
- -control functions
- -number of machines
- -standardization
- -modularization

The size and complexity of the NC-programs for machining of parts depends on the characteristics of the part design; number of different surfaces, the type of surfaces, the number of tools needed and machining data, like tooling speed, feed rate and depth of cut. But the cost is not related only to the size and complexity of the program. Modularization and standardization of sub-programs has made it possible to make long programs from easily available parts. This will reduce the costs for NC-programming.

The number of NC-programs is the same as the number parts in the family.

The size of the control software for the machine tools is determined by the rate of automatization. At one end you have systems, where the only automatic function is the supervising of the tooling function and automatic run down in case of disturbance. In addition to this you can have functions like alarm systems, automatic diagnostic of disturbances, correction of smaller disturbances and report systems.

The cost for these software packages is related to the total number of different control functions within the system. The number of machines is not important because the software can usually be transferred from machine to machine.

The software for operating machine tools and transport systems is usually a part of the package, and do not have to be separated as a special cost factor.

The software for production management has to be able to handel the tasks of managing the material, information and tool flows between all the machines in the system. The size and complexity of the software depends on number of machines, number of different part and production routs and the number of pallets and parts in the system.

The system control system can, in small FM-systems, be a logic units. This makes the need for software much smaller than if the control is performed by a micro or mini computer. The difference in performance is relevant, though. The complexity of the system control software is also dependant on the size of the system and the design of the control systems at machine and cell levels.

Where standardization and modularization can reduce the costs for software, can the need for redundancy have the opposite effect. Software redundancy mean that two or more software packages perform the same function, but their design is different.

2.4.4 Control costs

In addition to software the control of the system needs special hardware. These are censors in the machine tools, censors for recognition of parts and pallets, logic units or micro computers plus the hardware for transportation of the information.

The control cost is divided in the same way as the previous cost factors. Numbers of hardware equipment and the cost per hardware piece.

2.4.5 Transportation costs

The transportation cost in a FM-system can be divided into transport of work pieces and pallets, transportation of tools and transportation of scrap. The total cost is mainly related to the volume of transportation in the system, the need for parallel transporting of parts, scrap or tools and the size of the things that are transported.

The number of machines, the number of production steps per part and the routings of the parts between the different machines and the storage are the major factors affecting the number of movements per part. Since the transportation usually is done while the part is fixed to the pallet, the number of pallet movements is the most important issue when deciding on the design of the transportation system.

There will be a need for parallel transportation in the system if the machining time is short compared to the transportation time. Parallel transportation can also be needed to coordinate the flow of raw material, scrap and tools.

The cost of the equipment depends on the design. In a FMS is usually used either Automatic Guided Vehicles (AGV), Wire Guided Vehicles or transportation system based on High Storage. The price is also dependant on the size and the weight of the work pieces.

2.4.6 Storage costs

The storage of parts in the system is necessary to maintain a high utilization of the machines. WIP and raw parts fixed to pallets are needed to minimize the effect of bottlenecks, brakes and unmanned shifts. The last one of these is usually the biggest and the size of the storage is to a great extent depending on this feature.

The number and size of pallets do also affect the size of the storage.

2.4.7 Training costs

The training costs depends on the number of people being trained, the length of the training and the extra equipment needed.

The length of the training depends on the number of new functions and features in the FM-system. Here you can see a direct contact to the way the build-up stage of the project is organized. If the operators have participated in planning and building of the system it is possible to utilize the existing knowledge. This will decrease the need for training.

The training costs are also depending on the type of training given. Internal on-the-job training might be less expensive than bringing in external training people, but the purposes of and possibilities for different types can vary.

2.4.8 Machine costs

The machine costs can be divided in the same way as the tooling costs. The number of machines and the costs per machine. The cost per machine depends on the type of machine, the efficiency of the machine and the quality and tolerances of the machine. The setting of the price of the machine is also likely to vary between different vendors.

The number of machines depend on the characteristics of the production. The number of different machine tools is determined by the need for different machining functions and the number of functions one machine is able to perform. The number of one specific machine tool type depends on the need for machining time of the specific kind. The total time needed can be calculated on the basis of the production figures for every part and the figures of total production during a certain time period.

2.4.9 Implementation costs

A production system of the size of a FMS is not implemented in one day, one week or even one month. Usually the implementation lasts from a few months for small, highly standardized systems, to half a year or more for bigger and more complex systems. There are also cases where the implementation has lasted for about two years.

During this time there is a group of people working more or less continuously with the development of the system. Part of this work force is usually the vendors men and the cost of their work is usually included in the price of the hardware and software packages. The rest of the people are in-house personnel or external experts. They are giving birth to costs, that are not directly included in the costs for hardware or software.

Implementation costs can also include the extra equipment needed for the physical implementation of the system and the costs for re-arranging existing facilities to fit the new system.

3. THE EXISTING FORMULAS -CRITICISM

In this chapter we will have a look at the formulas in the existing model and compare these with the text in the previous chapters. The biggest problem here is the lack of documentation of the development of model. In addition we will present the test of the existing formulas based on data from a Finnish company.

(All time and cost functionsin this chapter are taken from (Kuula, Stam, 1989))

3.1 Time

$$TMIN \leq T + \Sigma r_i{*}v_i + T_d \leq TMAX \qquad (13a)$$

The formula for total time includes the total time the part spend in the machine tool, the total batch change time and the total disturbance time. The formula does not take into account the waiting time. In reality the disturbance timer is usually about 3 - 5 % of the total time, and the waiting time about 10 - 15 %.

$$T_{dj} = \sum_{i=1}^{n} d^g_{ij}{*}g_i + \sum_{i=1}^{n} d^b_{ij}{*}v_i + d^s_j{*}S_j - d_j^{PL}{*}PL \quad (j = 1,...,m) \qquad (10)$$

The formula for disturbance time takes into account the complexity of the part, the number of batches per period, the size of the software needed and personnel training. The three first components are seen to have a negative effect on the availability and the last one improves it. It seems that the designer of this formula wanted to restrict the number of factors to those which are available in a very early stage of the planning process. And it is true, that part complexity and batch changes put stress on the physical equipment in the automatic production system. The problem is that the formula does not take into account the characteristics of the production system and the organization around it. As was described earlier the product and it's complexity sets a lot of demands on the production system, but in the end the characteristics of the system decides what can be done and what can't and at what speed. The characteristics of the physical system, it's design and the organization of maintenance and operations will in the long run also decide the availability of the system. For instance the formula does not take into account the positive effect of control software on availability, the management of availability through manual or automatic functions nor the quality of the hardware.

If the previous assumption about the characteristics of the system is not true and the formula does include them in the form of parameters, the following questions rices. Why are only the software size and the training factor considered separately? If the parameters are statistical averages for different FM-systems, is this a better approximation than a qualified/ non-qualified estimation by a system designer? Is the variation in the effect of these factors on the availability, in one system and especially in different systems, so small, that it can be approximated by fixed constants?

3.2 Cost

$$C = C_M + C_L + C_P + C_S + C_T + C_O \qquad (1)$$

The total cost is a sum of machine costs, tool costs, pallet costs, software costs, overhead costs and transportation costs.
The total cost function does not take into account the costs for planning and implementing of the system. These are in reality a considerable part of the total costs, let alone the time related costs and opportunity costs during the implementation stage.

$$C_M = \sum_{j=1}^{m} e_j * M_j, \tag{2}$$

$$e_j = \sum_{i=1}^{n} e_{ij} * b_i * v_i * (T_{ij} + t_{ij}) \qquad (j = 1,...,m) \tag{3}$$

$$C_L = \sum_{i=1}^{n} q_{gi} * g_i + \sum_{i=1}^{n} \sum_{j=1}^{m} q_{ij} * l_{ij}, \tag{4}$$

$$C_P = \sum_{i=1}^{n} p_{gi} * g_i + \sum_{i=1}^{n} p_{bi} * b_i + \sum_{i=1}^{n} p_{vi} * v_i, \tag{5}$$

$$C_S = \sum_{i=1}^{n} s_{gi} * g_i + \sum_{i=1}^{n} (s+s_{vi}) * v_i + \sum_{i=1}^{n} \sum_{j=1}^{m} h_{ij} * l_{ij} + \sum_{j=1}^{m} s_{ej} * e_j, \tag{6}$$

$$C_T = u * V + \sum_{i=1}^{n} u_i * g_i + \sum_{i=1}^{n} u_{vi} * v_i, \tag{7}$$

$$C_O = C_{TR} + C_{RES} \tag{8}$$

Ranta assumes in his formulas, that all cost factors but the tooling costs and the training costs are dependant on the batch size and/or batch numbers. A critical study will show situations, where even these two factors are related to the characteristics of the system. The number of tools in a FMS will increase if a decrease in batch size means that the number of machine tools used will increase, and more frequent batch changes will put stress on the operators ability to maintain the availability of the system.

Taking a fast look at the formulas in 3.1 and 3.2 you get the feeling that the designer of the model has designed the model for use in a very early stage of the investment process. The main input is the requirement on the production from marketing and top management. Looking more closely at the model we find some technical data from the FMS. The tooling times for different parts in different machines and overhead time for every machine tool are needed. In addition there are the software size, the batch change time and data about personal training. These are a kind of data very much connected to the design of the FM-system, and at the same time this is often a very diffuse field for many people on the shop floor and in the production design department.

It seems that the formulas are built form a mix of information. Some information is available in a very early stage of the investment or design process, some needs a more comprehensive FMS-design. Further more, the cost formulas include parts, where information available in the later stage is built up and approximated by information from the early stages. The question arises; why not use data only from the later stage?

The generous use of parameters in the model and the lack of explanations of how they are calculated gives the feeling of a "black box" model. After having worked with the model for several months it is still unclear what these parameters represent and how they are calculated. This gives a very uncertain feeling. The fact that the formulas does not look like the reality behind them makes it even harder to understand and trust them. This will probably be a major obstacle for the practical use of the model. The FMS-designer wants and needs to see and understand the tools he is working with!

One more question: does a model based on statistics give as good a result as a model based on case by case estimated data?

3.3 Testing the formulas

Data from a finnish FMS was used for testing the formulas. To make the collection of data easier a questioner was developed (Appendix 3). It was based on the paper of Ranta & Alabian from 1988. The data was put into the formulas and the calculations were done manually. The results can be seen beneath.

The coefficients are taken from (Ranta, Alabian, 1988).

Disturbance coefficients and time constraints:

b Td min	G Td min	s Td min	pl Td min	SS mln line	PL h/per	Tmax thous min	Tmin thous min
3	40	0.05	3	1	100	316.8	158.4

Cost coefficients:

Sg ex4	Sv	Sl ex2	S*	Pg ex3	Pb ex3	Pv	Me	Rl ex2	Rg ex3	C*
0.5	20	3	10	10	3	200	100	5	10	10C

Cost constraints and efficiency coefficients:

Se	Kmin mln $	Kmax mln $	E1 th.	E2 mm/min th.	E3 th.	E4 th.
2	3	7	3	3	3	6

The input data from the company:

Part	b	vmin	G	L	Tb	T1+t1	T2+t2	V
1	18	335	4	12	0	9.5		6000
2	18	335	3	12	0	7.3		6000
3	18	185	3	12	0	6.0		3300
4	18	150	4	12	0	14.2		2700
5	18	185	3	12	0	7.3		3300
6	18	185	2	12	0	2.0		3300
7	18	225	2	12	0	2.0		4000
8	18	335	2	12	0	2.0		6000
9	18	185	2	12	0	2.0		3300
10	18	185	2	12	0	2.0		3300
11	18	145	6	12	0		25	3000
12	18	145	6	12	0		29	3000
13	18	145	4	12	0		13	3000
14	18	145	4	12	0		16	3000
15	18	145	3	12	0		7	3000

sumb	sumv	sumG	sumL
270	3030	50	180

PL = 105 h
SS = 1000 000 rows

The input of the value of the coefficients and the case data gives the following result:

Td = 40*50 + 3*3030 + 0.05*1000000 - 3*105 = 15 775 min

Lc = 180*500 + 50*10000 = 590 000 \$, (100 000 - 150 000 mk)

Pc = 10000*50 + 3000*270 + 200*3030 = 1916 000 \$, (504 000 mk)

Sc = 500*50 + 10*3030 + 20*3030 + 300*300 + 2*sumEj = 430 900 + 2*sumEj = 450 000 \$,

Mc = 100*10000 = 1000 000 \$, (4000 000 mk)

K = Mc + Lc + Pc + Sc + Oc + Tc = 1000 000 + 590 000 + 1916 000 + 450 000 + Oc + Tc =~ 4000 000 + Oc + Tc \$, (4500 000 mk)

The bracketed figure after the calculated value is the real value of the existing FMS. The value is given in Finnish marks. The exchange rate for US \$ to Fmk is 4.5 - 6.

As can be seen many of the calculated figures are far to large, some are more close to the truth. From this fact can be drawn a couple of solutions. There can be something wrong with the formulas, with the coefficients or with the input data from the case studies. Due to the lack of documentation it is very hard to tell exactly what has to be changed. A quick test of the structure of the formulas is possible by changing the input data. This gives some idea of how they work.

4. A NEW APPROACH

The model should support the FMS designer in estimating the needed input data. The new idea is that the designer gets a qualified grip on the data and the results by doing the major part of the job him self. He will have a greater understanding for the function of the model and for the results. He is also more likely to trust them when he is able to evaluate them in a rational way. No "black boxes" or magic!

The formula for total time is very simple and understandable. It consists of easily defined parts and even the mathematical operations are simple. The only thing that might be considered is adding some more parts. A component for waiting time might improve the model.

The cost formulas in the existing model are not consistent with the new approach. Here we need some major changes. To make the formulas as simple and real process look-a-like as possible, we start by looking at the investment objects and it's price. To make it more visible we are going to take the tooling costs as an example. How can the costs for tools be divided? Let's start by dividing the total cost into actual tooling costs and overhead costs. The actual tool costs can be distributed per tool, in other words the tool costs is the sum of the cost of each tool. To calculate this you need to know what tools are needed. This depends on mainly two factors: the need for different tools to machine all the shapes needed in the part family, and the effect of volume, flexibility and tool brake down on the number of each tool type.

In addition the price of the tools is needed. In case of standard tools these can easily be found in vendor catalogues. The cost for special tools can usually be estimated by tool producers in or out side the firm.

At this stage we need to take a look at the model in (Ranta, Alabian, 1988) and (Stam, Kuula, 1989). For the optimization process we need a mathematical definition of the costs. The variables are the batch size and the number of batches for every product or part. We can define the cost for the tools (Lc) as a function of cost per individual tool (Lk) and number of pieces (n). The number of pieces is a function of number of different tools (nd) and the effect of volume (V), batch size (b) and number of batches (bn), tool brake down (tb), standardization (st) and modularization (mo).

$$Lc = f(Lk, n(nd, V, b, bn, tb, st, mo))$$

Lk and nd are quit easy to find or calculate from vendor catalogs and product drawings. The problem is to decide the effect of v, b, bn, tb, st and mo on the number of tools. In the model there is assumed, that constraints can be given for the variables b and bn. This means that only a sample of options has to be studied. Here we assume, that the designer has one rough FMS-design in mind. This design is able to fulfill one option inside the constraints given. By changing the design to fit a new set of b and v the designer finds the dynamics of the cost structure for the tools.

The effect of production volume (v) per time period on the number of tools is a non-linear problem. The tool management inside the production system will affect the number of tools. The number of machines performing the same machining function simultaneously is one definite indicator of how the volume will affect the number of tools. But also if they don't work in parallel the number of machine tools will be important. A part of the tool costs can be translated into transport and management costs if a integrated tooling system for all the system is used.

In this case the designer has to look at the design in question and make approximations of how the volume will affect the number of tools in this specific case. The same thing goes for standardization, modulariztion and safety marginals for broken tools. Approximations can be made on the bases of company policy or rules.

The new approach has yet to be developed for the other cost factors and the concept has to be tested and improved. The idea of this paper is to have a critical review of the existing model and to give some options for improvement. A lot of job has to be done and many new options has to be reviewed before the project can be finished.

5. CONCLUSIONS

It seems quite obvious that the existing model needs modification. The test results are not what was expected and in this paper has been presented criticism to the structure of the formulas in the model. Some new ideas are shortly presented.

It can be argued that the new approach needs a lot more information and work than the mathematical formulas in the original model. This is probably true. But it dose not mean, that the design process has to be driven further before you get the needed data. In the original model the planner was supposed to feed the system with tooling time data from every machine and part. This means that he has to have a clear idea of what he is doing, how he is going to do it and with what means. In other words he has to know quite well what kind of equipment he is going to use. The data needed for this approach will certainly be available at this stage of the planning process.

The suitability of the new approach has yet to be tested and a lot of job remain to be done before a final solution is found. However, the speculations and discussions around this matter has given some thoughts about the model and modelling in general, that might prove helpful in future research. Listed beneath are some lessons learned during this work.

- Make the model as simple as possible and let the structure be a mirror of the reality

- A good enough mathematical approximation can prove to be just as complicated or even more complicated than doing the calculation on the basis of real data.

- The estimating of figures and numbers is dependant on the specific experience of the model user and all figures can not equally easily be estimated. The role of the model is to help the planner to find a good estimation.

- The model should ask for information in a structured way. The needed data should be divided into easily found and understood parts.

- Hints based on experience from similar projects should be given to the planner

- A good estimation from an experienced planner can take into account many aspects, that are very difficult to approximate in mathematical formulas.

- Do not put into the model things the user can not understand or see

- Avoid mixing different kind of information, information from different stages of development or time periods. If different kind of information is used see to that they are clearly separated and defined.

- No model gives the right answer! Only through proper understanding of the structure and function of the model can the results be properly used!

- The mathematical formulas are included in the purpose to support the planner in approximating the needed figures. If the figures are known the formulas should not be used and the results gained from the model should be re-evaluated and modified if the planner feels that it is necessary.

REFERENCES

M. Kuula and A. Stam, "A Nonlinear Multicriteria Model for Strategic FMS Selection Decisions," WP-89-062, International Institute for Applied System Analysis, Laxenburg, Austria, 1989.

J. Ranta and A. Alabian, "Interactive Analysis of FMS Productivity and Flexibility," WP-88-098, International Institute for Applied System Analysis, Laxenburg, Austria, 1988.

A. Stam and M. Kuula, "Selecting a Flexible Manufacturing System Using Multiple Criteria Analysis," WP-89-048, International Institute for Applied System Analysis, Laxenburg, Austria, 1989.

APPENDIX 1 (Kuula, Stam, 1989)

Formulas:

$$C = C_M + C_L + C_P + C_S + C_T + C_O \tag{1}$$

$$C_M = \sum_{j=1}^{m} e_j * M_j, \tag{2}$$

$$e_j = \sum_{i=1}^{n} e_{ij} * b_i * v_i * (T_{ij} + t_{ij}) \qquad (j = 1,...,m) \tag{3}$$

$$C_L = \sum_{i=1}^{n} q_{gi} * g_i + \sum_{i=1}^{n} \sum_{j=1}^{m} q_{ij} * l_{ij}, \tag{4}$$

$$C_P = \sum_{i=1}^{n} p_{gi} * g_i + \sum_{i=1}^{n} p_{bi} * b_i + \sum_{i=1}^{n} p_{vi} * v_i, \tag{5}$$

$$C_S = \sum_{i=1}^{n} s_{gi} * g_i + \sum_{i=1}^{n} (s + s_{vi}) * v_i + \sum_{i=1}^{n} \sum_{j=1}^{m} h_{ij} * l_{ij} + \sum_{j=1}^{m} s_{ej} * e_j, \tag{6}$$

$$C_T = u * V + \sum_{i=1}^{n} u_i * g_i + \sum_{i=1}^{n} u_{vi} * v_i, \tag{7}$$

$$C_O = C_{TR} + C_{RES} \tag{8}$$

$$T_j = \sum_{i=1}^{n} (T_{ij} + t_{ij}) * b_i * v_i, \qquad (j = 1,...,m) \tag{9}$$

$$T_{dj} = \sum_{i=1}^{n} d^{g}{}_{ij} * g_i + \sum_{i=1}^{n} d^{b}{}_{ij} * v_i + d^{s}{}_{j} * S_j - d_j^{PL} * PL \qquad (j = 1,...,m) \tag{10}$$

$$T_j + T_{dj} \leq T_{jMAX} \qquad (j = 1,...,m) \tag{11}$$

$$T_{jMIN} \leq T_j + T_{dj} \leq T_{jMAX} \qquad (j = 1,...,m) \tag{12}$$

$$TMIN \leq T + T_d \leq TMAX, \tag{13}$$

$$TMIN \leq T + T_d + \sum_{i=1} r_i * v_i \leq TMAX \tag{13a}$$

APPENDIX 2 (Kuula, Stam, 1989)

Concise list of decision variables and model parameters used in the paper:

Decision Variables:	**Description:**
b_i	batch size, part i
v_i	number of batches produced per period, part i

Indices:	**Description:**
$i \in \{1,...,n\}$	the set of parts
$j \in \{1,...,m\}$	the set of machines

Model Parameters:	**Description:**
c_{PL}	training costs per employee per period
e_{ij}	efficiency of machine j on part i
e_j	efficiency of machine j
g_i	measure of complexity of part i
l_{ij}	number of tools needed on machine j to produce part i
M_j	direct investment costs per unit produced per period, machine j
PL	number of employees to be trained per period
S_j	complexity of the software needed for machine j
T_{ij}	unit tooling time of part i on machine j
t_{ij}	unit overhead time of part i on machine j
T_{jMAX}	maximum minutes machine j can operate per period
T_{jMIN}	required minimum minutes machine j should operate per period
T_{MAX}	maximum minutes all machines combined can operate per period
T_{MIN}	required minimum minutes all machines combined should operate per period
T_j	total time machine j is in operation per period
T_{dj}	total non-available (disturbance) time of machine j per period
T	total time all machines combined are in operation per period
T_d	total non-available (disturbance) of all machines combined per period
V_i	production quantity of part i per period
V	total production capacity per period
w_i	relative importance weight of producing part i
y	planed lifetime of the system
L	discounted labor, maintenance and improvement costs per period

of the system

r_i	unit batch change time for part i

Scaling Coefficients for Contribution to

Model Parameters:	**Description:**
d^{g}_{ij}	non-availability of complexity of part i produced on machine j
d^{b}_{ij}	non-availability of batch size of part i produced on machine j
d^{s}_{j}	non-availability of software size and complexity for machine j
d^{PL}_{ij}	non-availability of personal training for part i on machine j
q_{ij}	total costs of number of tools needed, l_{ij}
q_{gi}	tool costs of complexity of part i
p_{gi}	parts pallets costs of complexity of part i
p_{bi}	parts pallets costs of batch size of part i
p_{vi}	parts pallets costs of number of batches produced of part i
h_{ij}	software costs of number of tools needed, l_{ij}
s_{gi}	software costs of complexity of part i
s	software costs of total number of batches produced
s_{vi}	software costs of number of batches produced of part i
s_{ej}	software costs of efficiency of machine j
u	transportation costs of total production capacity
u_i	transportation costs of complexity of part i
u_{vi}	transportation costs of number of batches produced of part i
f_{gi}	flexibility of complexity of part i
f_{vi}	flexibility of production volume of part i
f_{bi}	flexibility of batch size of part i

Cost Component:	**Description:**
C_M	machine costs per period
C_L	tool costs per period
C_P	parts pallet costs per period
C_S	software costs per period
C_T	transportation costs per period
C_O	other costs per period

APPENDIX 3

VTT/SÄH 25.04.89
Magnus Simons

0. COMPANY

I. THE FM-SYSTEM

1) product

2) machine tools, other machines and control equipment

3) organization

II. FACTORS

V = annual production volume
Vmin = minim. annual production volume
Vmax = maxim. annual production volume
vi = number of batches
bi = batch size
Tij = actual tooling time
tij = overhead time (changing, waiting, checking, repairing, etc.)
Tjmin = minimum time per machine tool
Tjmax = maximum time per machine tool
T min = minimum time, all the system
T max = maximum time, all the system
Tbi = batch change time
m = number of machines in system
N = number of parts in family
Td = technical non-availability time
Gi = complexity factor of product i
- surfaces to be machined
- tolerance

- material
- standardization
- physical dimensions
- number of tools needed
- fixing
- difficult shapes

SS = software size factor
- number of rows
- modularization
- standardization
- memory space
- language

PL = personnel training factor
- number of hours per person
- educational background of the workers
  way of choosing people for the job

K = cost factor

Kmin = minimum costs for system

Kmax = maximum costs for system

Mc = machine costs

Ej = efficiency of machines
- effect
- feed

Lc = tooling costs

Lkj = tool specification and numbers

Pc = pars pallet costs

Sc = software costs

L = number of tools

Tc = transportation costs

Oc = training costs

Other factors:

Tdi(G) = technical non-availability time, complexity factor

Tdi(b) = technical non-availability time, batch change factor

Td(s) = technical non-availability time, software factor

Td(PL) = technical non-availability time, personnel training factor

Mej = machine costs coefficient related to efficiency

Rlj = tool costs coefficient related to tools complexity, numbers
Rgi = tool costs coefficient related to part complexity
Pgi = parts pallets cost coefficient related to part complexity
Pbi = parts pallets cost coefficient related to batch size
Pvi = parts pallets cost coefficient related to number of batches
Sgi = software cost coefficient related to software complexity
Sbi = software cost coefficient related to batch size
S*vi = software cost coefficient related to capacity
Sli = software cost coefficient related to tools management
Sej = software cost coefficient related to efficiency
O* = training cost coefficient

III. STARTING POINT OF THE DESIGNER'S

1) product, product family
2) old production
2) machine tools, tools
3) transportation
4) control
5) organization
6) capacity
7) flexibility
8) availability, utilization rate

IV. USEFULNESS OF SIMULATION MODEL

V. APPENDIX (DRAWINGS, SCHEMES, PHOTOGRAPHS)